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Cold flow investigations of a plug flow reactor with internal recirculation for pressurized chemical looping

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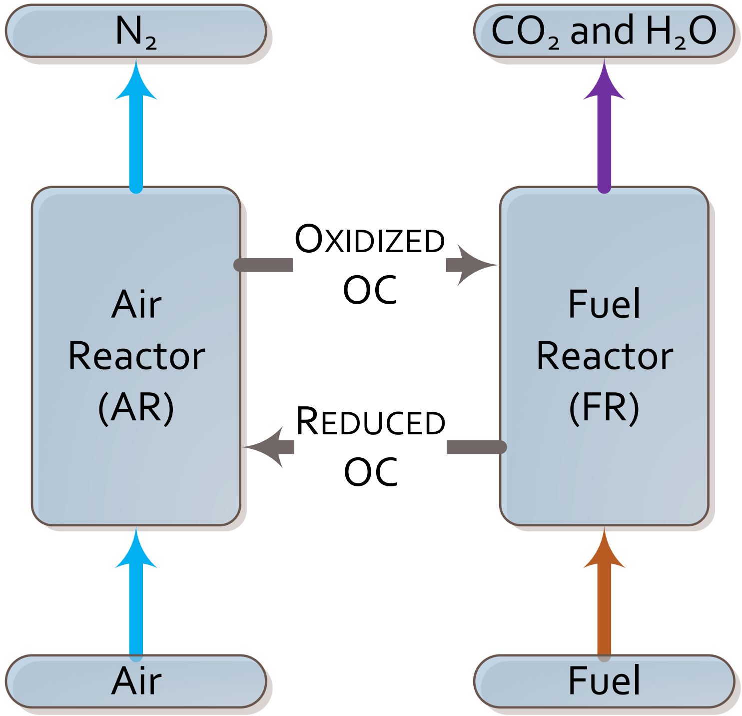
Canada

Outline

- Pressurized chemical looping
- Plug flow reactor with internal recirculation (PFIR)
- Design approach & data needs
- Circulation rate measurement challenges
- Method evaluation
- Status & future work

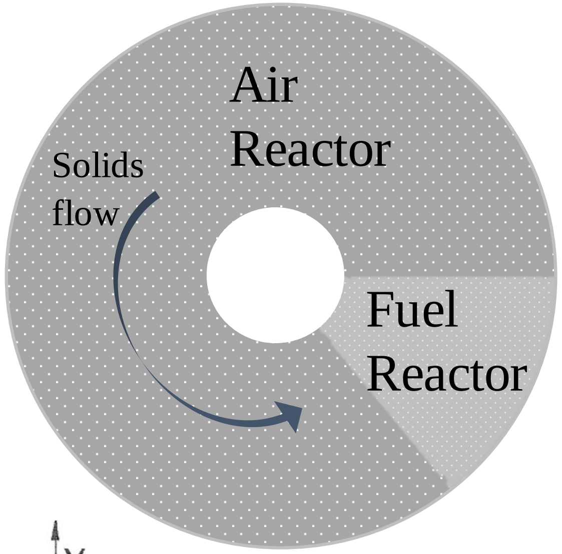
Pressurized Chemical Looping (PCL)

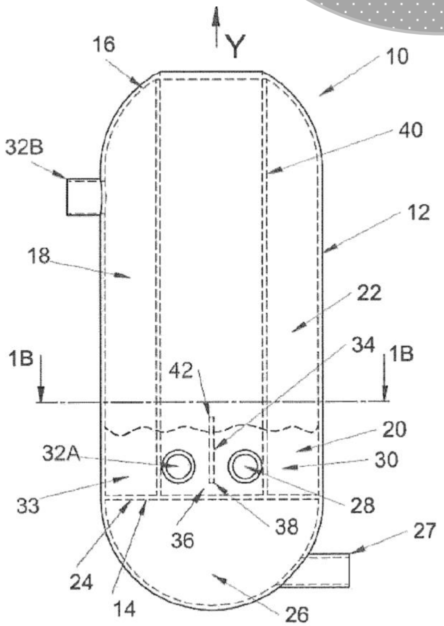
- Technology for burning fuels to produce **heat** with inherent separation of CO_2
  - Oxygen carrier composed of metal oxides for redox reactions
  - Direct contact between fuel and air is avoided
  - O_2 is transferred *via* an **oxygen carrier** (OC)
  - High purity CO_2 product achieved via drying of flue gas stream
  - Achieved with dual fluidized beds (air reactor and fuel reactor)
- CanmetENERGY is currently developing a 600 kW^{th} pilot plant
- Technology to provide zero-emission heat or hydrogen to industry



PFIR

- CanmetENERGY & Hatch Ltd. are collaborating on the design of the PCL reactor system
- Hatch's patented plug flow reactor with internal recirculation (PFIR) is a good fit for PCL
  - Annular reactor segmented into 2 bubbling fluidized beds:
    - Air reactor and fuel reactor
  - Enables large flowrates of solids between the two reactors
    - Move oxygen and heat between air and fuel reactors
    - Solid movement enabled by angled jets at the distributor
  - Single reactor vessel reduces capital costs and process complexity

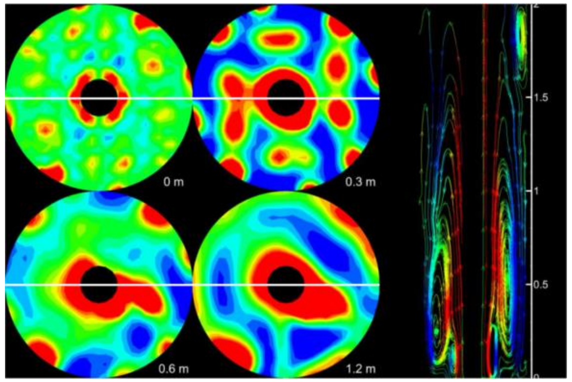


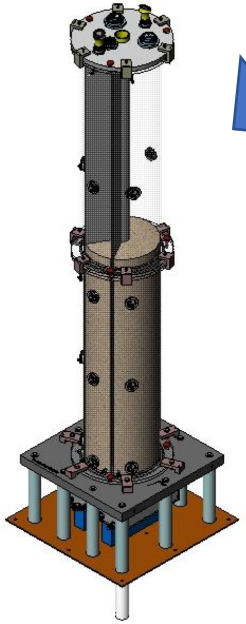


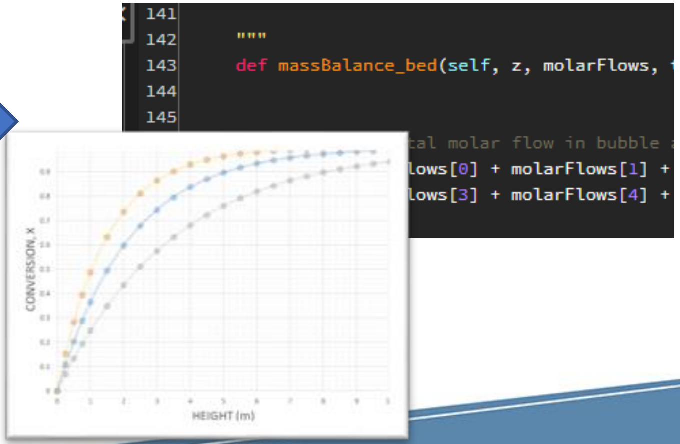
Adham, Kamal; Harris, Christopher; Kokourine, Alexandre. Plug flow reactor with internal recirculation fluidized bed. WO2015/188267 A1, World Intellectual Property Organization, 17 December 2015.

Design Approach

- Three pronged approach to reactor design incorporating modeling and experimental validation:
  - Two-phase theory 1D reactor model
    - Kinetics, gas/solid reaction models
  - Barracuda CPFD
    - Fluidized bed performance, geometry
  - Cold flow experimentation
    - Model validation, performance data

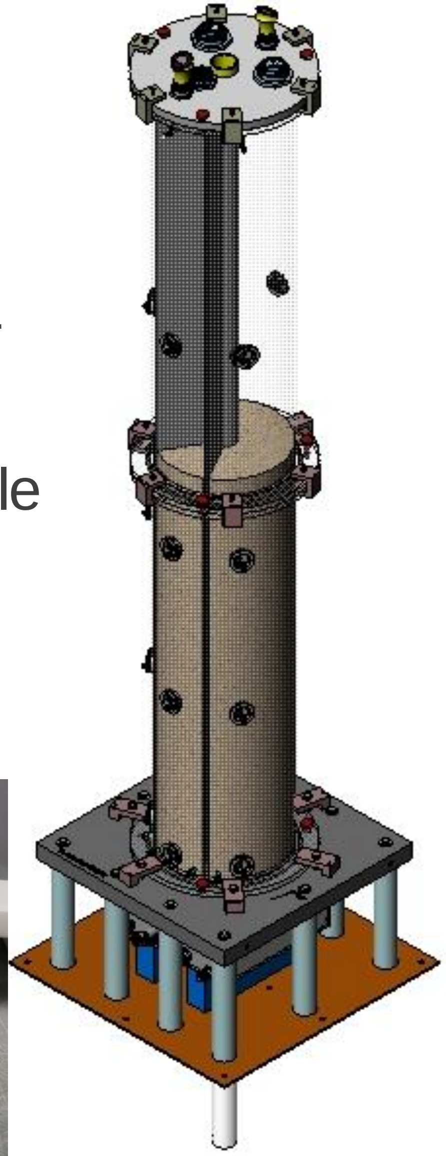






The Cold Flow Model

- Large cold model under development to optimize PFIR design for PCL process
  - Generate data to validate CPFD and reactor models
- Cold model built out of plastic to minimize signal degradation for particle tracking methods
- Key performance indicators:
  - Circulation rate of bed material between air and fuel reactors
  - Residence times of bed material in each reactor
  - Solids mixing
  - Gas mixing at the reactor boundaries
- Test conditions:
  - Superficial velocity: 0.0 - 0.85 m/s
  - Bed material: Aluminum oxide, 350 μm, 3950 kg/m^3
  - Atmospheric temperature and pressure

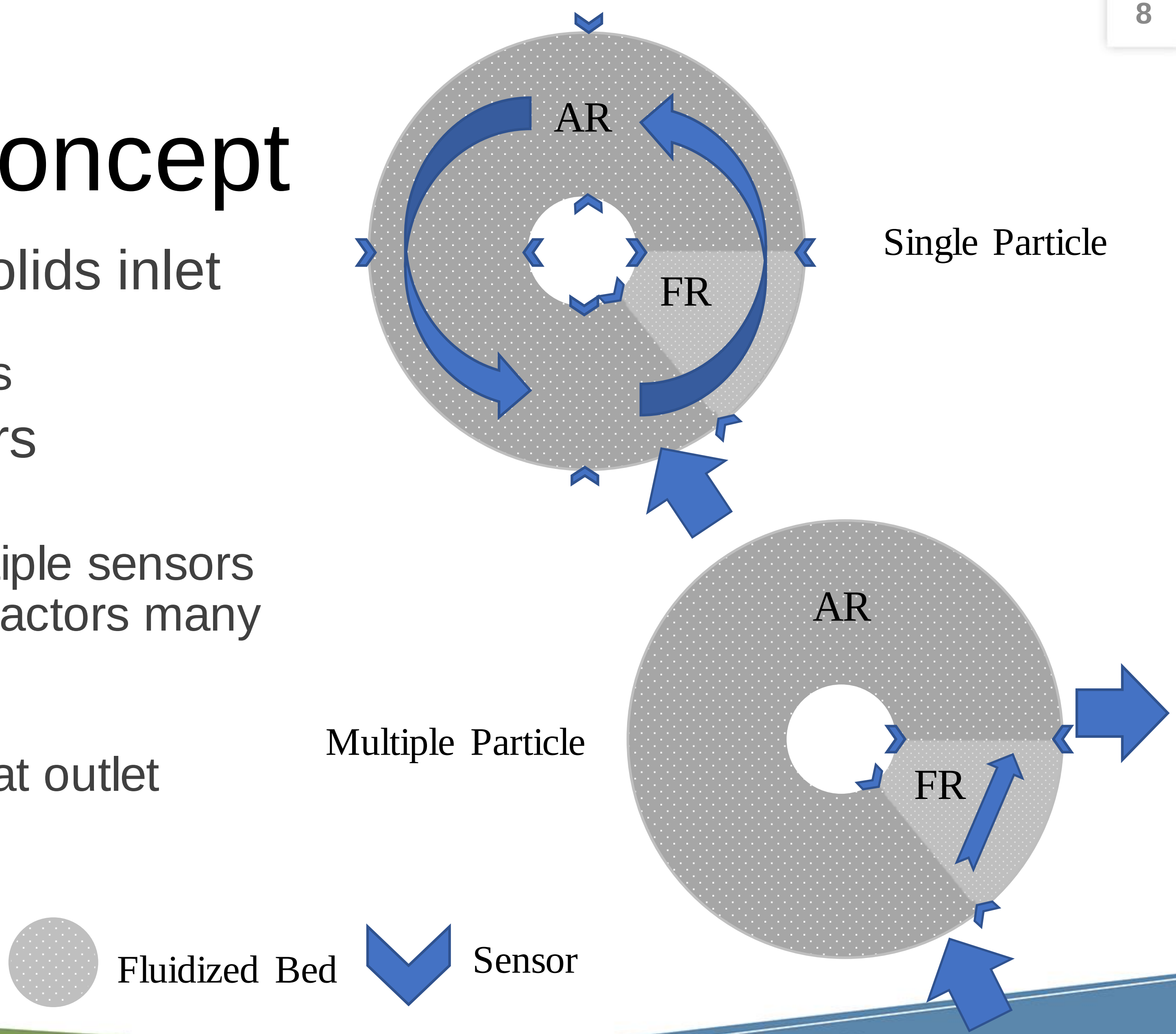


Circulation Rate Measurement

- Priority parameter for model validation and hot pilot design
- Objective:
  - Select a measurement technique for the cold flow model to:
    - Measure circulation rate of bed material between two reactors
    - Measure residence time distribution in each reactor
- Challenges:
  - Measurement devices cannot interfere with solid and gas flow patterns in the PFIR
  - No loop seals, return legs or other exterior flow control devices
    - ‘Bucket method’ not feasible
  - Dense bed material (~4000 kg/m^3) and high circulation rates
- Particle tracer methods:
  - Several techniques (magnetic, radioactive, inductance, etc.)
  - No clear front runner given application

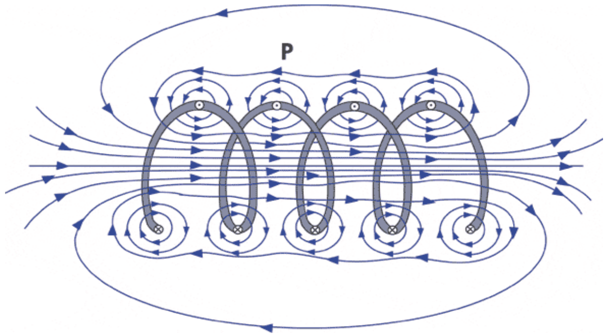
Particle Tracking Concept

- Inject a tracer particle at the solids inlet flow plane
  - Single particle vs. multiple particles
- Measure signal on inlet sensors
- For single particles:
  - Monitor position of tracer with multiple sensors
  - Allow particle to transit between reactors many times to get RTD
- For multiple particles:
  - Monitor concentration of particles at outlet plane
  - Collect particles and re-inject



Inductance Particle Tracking

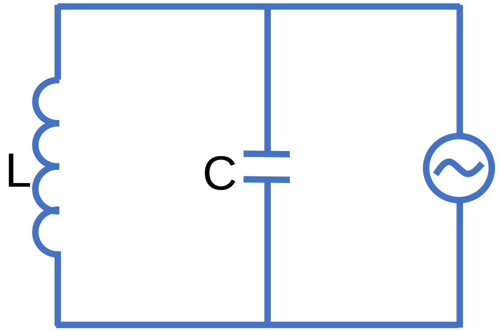
- Track ferromagnetic or conductive tracer particles using an inductor coil
  - Tracer candidates: steel, aluminum, iron
- Concentration of tracer particles in the sensing area of the coil correlates to coil inductance
  - Tracer changes magnetic permeability in region near coil, changing the field and therefore the coil's inductance
- Coils typically installed around the exterior or return legs or loop stand pipes
  - Field most dense in the interior of the coil, producing the strongest signal
  - Lack of solid transfer systems in PFIR is a challenge



https://www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/Physics/CoilField.htm

Inductance Particle Tracking

- Flat, printed circuit board coils investigated
  - Based on Texas Instruments inductance-to-digital converters
  - Multiple sensors can be mounted at the inner and outer perimeter of the PFIR annulus
- Experiments completed to determine coil design requirements and performance of various tracer candidates



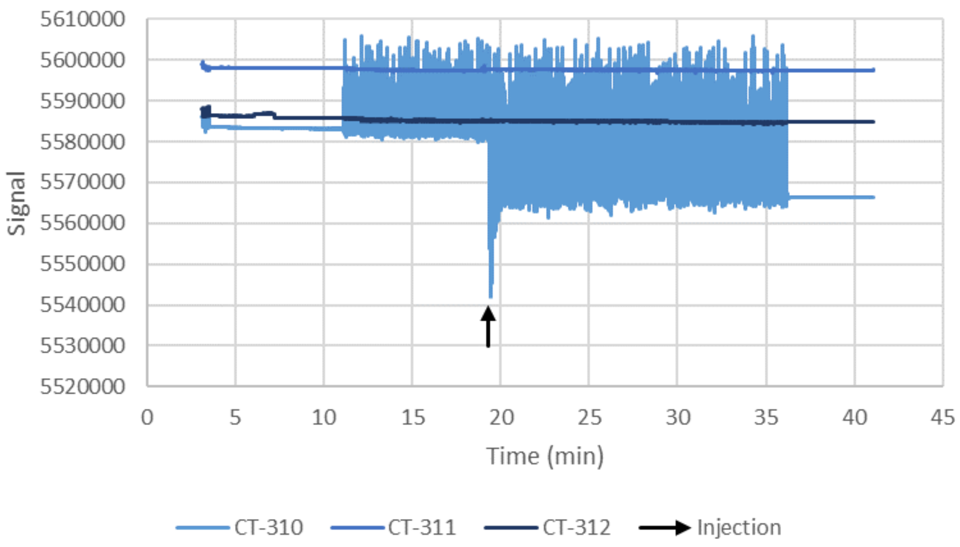
Sensor frequency

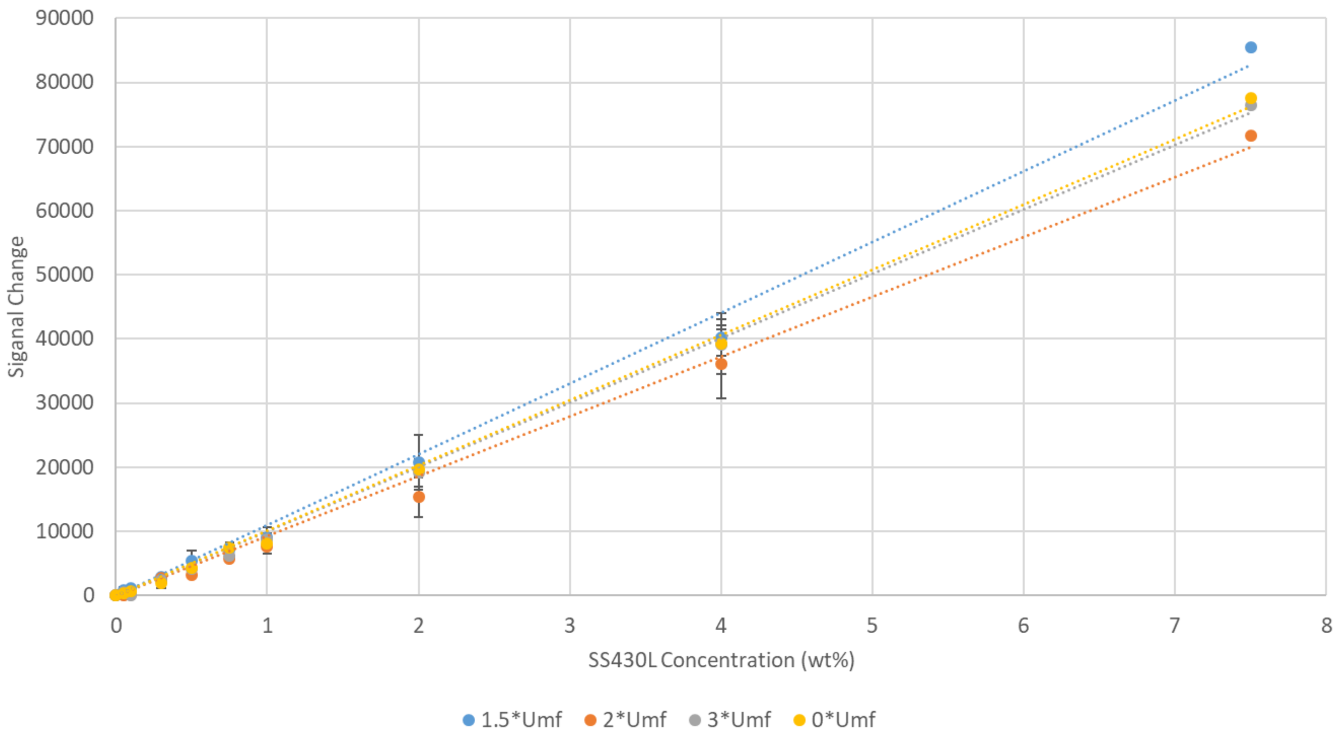
$$f = \frac{1}{2\pi\sqrt{LC}}$$

Inductance Capacitance

Inductance Particle Tracking

- Tracer: 430L stainless steel
- Bed material: alumina zirconia
- Fluidizing gas: air
- Velocity range: 0-3 U/Umf





Inductance Particle Tracking

Advantages

- Tracer particles can be selected to have similar fluidization behaviour to bed material
- Flat coils integrate well into the PFIR geometry
- May be able to measure bubble properties
- Measure concentration of tracer to allow rapid RTD measurement

Challenges

- Bed material must be non-magnet and non-conductive to minimize signal noise
- Large amount of tracer required to achieve significant signal to noise ratio
- Significant development time required to deploy the PCB coil sensors

Magnetic Particle Tracking

- Magnets are used as tracer particles and their position and orientation is tracked by a set of anisotropic magnetoresistive (AMR) sensors
- Collaborating with RISE Research Institute of Sweden to determine minimum magnet size feasible and sensor layout for PFIR
- PFIR implementation:
  - Single magnet tracer
  - Sensors to cover planes between reactor zones
  - Track tracer magnet as it passes each plane
  - Log time in each reactor

Magnetic Particle Tracking

Advantages

- Well developed technique
- Can measure both position and orientation of magnet, given enough sensors are present
- Can be used for mixing studies with enough sensors

Challenges

- Tracer particle must be a magnet; challenging to match fluidization behaviour of bed material
- Limited sizes of magnets commercially available
- Segregation of the tracer particle likely
- Commercially available systems not compatible with small magnets required

Radioactive Particle Tracking

- Radioactive material is tracked using multiple scintillation detectors to detect gamma rays from decay of tracer
- Collaborating with University of British Columbia on calibration techniques
- PFIR implementation:
  - Single radioactive tracer
  - Sensors to cover planes between reactor zones
  - Track tracer as it passes each plane
  - Log time in each reactor

Radioactive Particle Tracking

Advantages

- Well developed technique
- Tracer can be tailored to match bed material fluidization behavior
- Commercially available sensors
- Can be used for mixing studies with enough sensors

Challenges

- Difficult to separate out tracer particle in-situ
- Dense bed material may result in limited signal strength due to attenuation
- Requirement to source and handle radioactive tracer

Current Status & Future Work

- Status:
  - Cold flow model under construction, testing to start in late summer
  - Inductance particle tracking with PCB coils to continue development, however not planned to be used in first tests in the cold model
  - Magnetic particle tracking for PFIR in development in collaboration with RISE Research Institutes of Sweden
  - Radioactive particle tracking for PFIR in development in collaboration with the University of British Columbia
- Future work:
  - Measure circulations rates with both RPT and MPT in the same test unit
  - Develop data workflows to use radioactive and magnetic tracking data to validate CPFD models

Thank you!

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